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Assessment of Backfill Hydraulic Conductivity in an Instrumented Soil-Bentonite Cutoff Wall

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Abstract. The objective of this paper is to present a comparison of measured hydraulic conductivities (*k*) for soil-bentonite (SB) backfill within a 60-m-long section of a 200-m-long, 7-m-deep cutoff wall constructed and instrumented for studying SB backfill properties and variability at the field scale. Backfill *k* was measured using flexible-wall tests (70-mm diameter) on remolded specimens prepared from surface grab samples collected during construction; flexible-wall tests on undisturbed specimens collected from the wall; larger-scale rigid-wall tests (150-mm diameter) on remolded specimens prepared from grab samples; and slug tests conducted within the wall. Applied effective stresses in the laboratory tests ranged from 4–35 kPa, encompassing the range of *in-situ* stresses measured in the backfill after load transfer and consolidation (8–13 kPa). The results indicate low spatial variability in *k* for a given test type, consistent with the observed homogeneity of the backfill. Modest variability in *k* was observed among the different test types, with the slug tests and rigid-wall tests generally yielding slightly higher *k* relative to the flexible-wall tests at field-representative stresses.

Keywords: Cutoff wall · Hydraulic conductivity · Slug test · Soil-bentonite

1 Introduction

Soil-bentonite (SB) cutoff walls, or vertical barriers backfilled with bentonite-admixed soil, are widely used in the US for long-term hydraulic and geoenvironmental containment applications. In these applications, the effectiveness of the wall is governed largely by the hydraulic conductivity (k) of the SB backfill, and designs generally specify a low backfill *k* (e.g., $k < 10^{-6}$ or 10^{-7} cm/s). During construction, backfill *k* typically is verified by means of a quality control/quality assurance (QC/QA) testing program in which small-scale (70–100 mm diameter) laboratory *k* tests (usually flexible-wall tests via ASTM D5084) are conducted on remolded specimens prepared from surface grab samples of field-mixed backfill. The results of these tests may not be representative of the *in-situ* backfill *k*, particularly if the applied stress state on the specimens is not representative of the *in-situ* stress state. The *in-situ* stress distribution within an SB wall is rarely measured, difficult to predict, and impacted by complex load transfer mechanisms. Also, laboratory tests on remolded specimens are inadequate for verifying the absence of defects created while backfilling, or for determining post-construction changes in *k*.

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These limitations of conventional QC/QA programs are compelling reasons for conducting post-construction assessments of the *in-situ* *k* of SB cutoff walls based on field testing and/or laboratory testing of undisturbed specimens recovered from the wall. Such assessments are rarely performed in engineering practice and have been conducted only to a limited extent in research studies. A notable study was conducted by Britton et al. [1], who evaluated field and laboratory methods to measure *k* of a small (20.4-m-long, 2.8-m-deep, 0.6-m-wide) pilot-scale SB cutoff wall. They found that laboratory *k* values obtained from remolded specimens were consistently lower than laboratory *k* values obtained from undisturbed specimens and lower than *k* values obtained from *in-situ* measurements (i.e., slug and pumping tests). The results of the study [1], although limited in size and scope, indicate that a more comprehensive investigation of field *k* assessment methods for full-scale SB cutoff wall installations is warranted.

Researchers at Bucknell University have constructed and instrumented a 200-m-long, 7-m-deep, and 0.9-m-wide SB cutoff wall near Lewisburg, PA for the purpose of studying the SB properties, behavior, and variability at the field scale. The primary objective of this paper is to present the results of a post-construction assessment of backfill *k* within a 60-m-long section of the wall and to compare field (*in situ*) measurements of *k* based on slug tests with laboratory measurements of *k* performed on both remolded and undisturbed specimens. Lessons learned from this study pertaining to the use of slug tests to measure backfill *k* in full-scale SB cutoff wall installations are discussed.

2 Background

The SB cutoff wall site is located in Montandon, PA, approximately 3 km east of the Bucknell campus (see Fig. 1a and b). The wall was installed in an alluvial deposit on the property of a local sand and gravel quarry, adjacent to a natural wetland known as the Montandon Marsh (Fig. 1c). The wall was constructed using conventional slurry trenching, with sodium bentonite slurry (5–6 wt% bentonite) used for hydraulic shoring and backfill mixing. The backfill was prepared by mixing imported base soil (stockpiled clayey sand excavated from other areas of the site) with slurry to achieve a slump of 75–150 mm prior to backfilling [2]. Quality control testing included daily soundings of the trench bottom, slurry quality testing (viscosity, filtrate loss, density, and pH), and backfill slump. Also, grab samples (10–20 L) of the field-mixed backfill were collected at every 10 m along the length of the wall, for a total of 20 grab samples.

Stationing was used to delineate position along the wall alignment, with the southern end of the wall located at Station 0 + 06 m and the northern end at Station 2 + 07 m. This study considers the 60-m portion of the wall extending from Station 0 + 50 m to Station 1 + 10 m (Fig. 1d). In this section, monitoring wells and inclinometers were installed adjacent to the wall at Stations 0 + 60 m and 0 + 90 m prior to wall construction, and earth pressure cages (RST Instruments, Maple Ridge, BC, Canada) were embedded in the backfill at Stations 0 + 75 m and 0 + 84 m to monitor the three-dimensional stress state in the backfill. The sensors on each cage include three pressure sensors to measure vertical and horizontal (longitudinal and transverse) total stresses, a vibrating-wire piezometer to measure pore pressure, a biaxial tiltmeter and magnetic compass to monitor the cage orientation, and a thermocouple. Three earth pressure cages were embedded in the backfill at different depths (2.4, 4.4, and 6.4 m) at Station 0 + 84 m, and one cage was embedded at a depth of 6.2 m at Station 0 + 75 to provide replicate measurements of stress near the trench bottom. Additional details are provided by Malusis et al. [2].

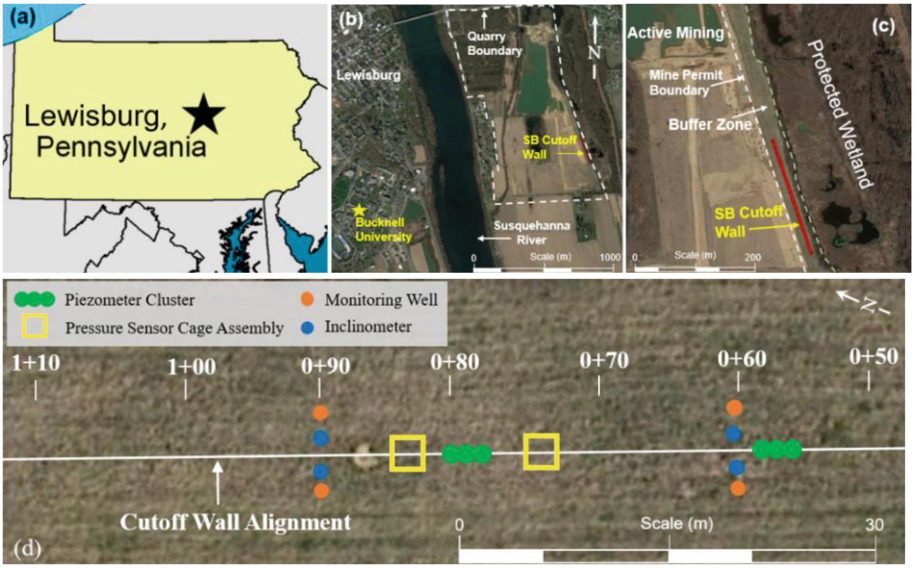

Fig. 1. (a, b) General site location; (c) aerial photo showing where the cutoff wall was constructed; (d) close-up plan view of study area with instrumentation.

The total vertical stress (CT_z), horizontal stresses (a* = transverse; *ay* = longitudinal), and pore pressure (u) measured in the wall at Station 0 + 84 m (depth z = 6.4 m) over ~19 months (575 days) are shown in Fig. 2a. At completion of backfilling, the total stresses were approximately equal to the weight of the overlying backfill and were nearly isotropic, consistent with the fact that the backfill is placed as a thick, viscous liquid. Over time, as the backfill underwent primary and secondary consolidation, total stresses declined as the load was transferred through shear to the sidewalls of the trench. Likewise, pore pressures dissipated along a similar timeline as the total stresses, yielding low effective stresses that increased slightly during the first year after construction but have now stabilized at 8–13 kPa (see Fig. 2b–d). These effective stresses are considerably lower than would be expected by assuming a geostatic stress distribution in the backfill, but are reasonably consistent with stress estimates given by predictive stress models developed for SB cutoff walls in which load transfer to the trench sidewalls is taken into account [e.g., 3].

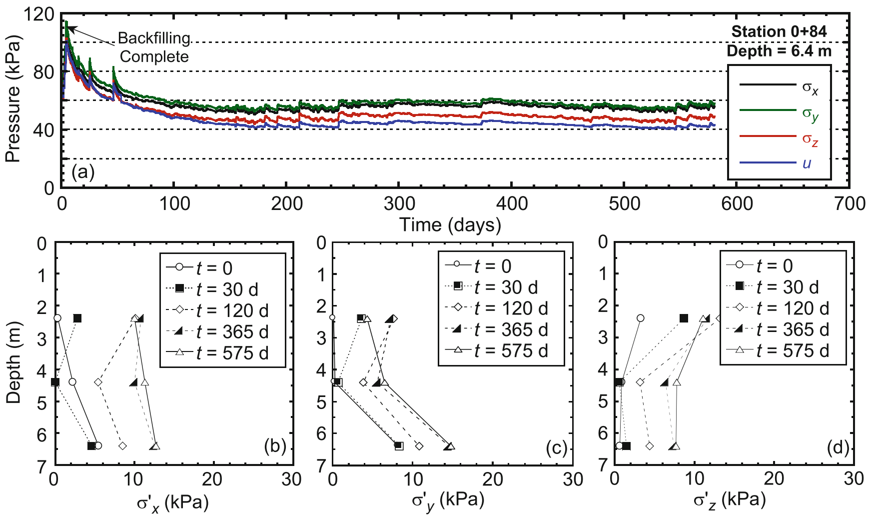

Fig. 2. (a) Total stresses and pore pressures measured over time at Station 0 + 84 m, depth = 6.4 m (σ_x = transverse horizontal stress; σ_y = longitudinal horizontal stress; σ_z = vertical stress; u = pore pressure; (b, c, d) distributions of effective stress (σ_x', σ_y', and σ_z') versus depth (t = time after completion of backfilling).

3 Materials and Methods

3.1 Laboratory Tests

For this study, seven flexible-wall *k* tests (ASTM D5084 Method C) were performed on remolded specimens (diameter = 70 mm, length = 71–85 mm) prepared from surface grab samples of the field-mixed backfill collected at each 10-m interval along the test section shown in Fig. 1c (i.e., Stations 0 + 50 through 1 + 10 m). The specimen preparation procedures are the same as those described elsewhere [4]. Also, undisturbed backfill samples were recovered from the wall at Stations 0 + 67 m (z = 2.1 m), 0 + 90 m (z = 0.75 m), and 1 + 1.0 m (z = 2.0–3.5 m) using Shelby tubes with a piston sampler. These specimens were tested in a similar manner as the remolded specimens. The loading sequence for each specimen included four stages of isotropic consolidation at average effective stresses ranging from 6.9 to 34.5 kPa. The specimens were permeated with tap water at each loading stage until inflow/outflow balance and steady *k* were obtained, as required by ASTM D5084.

In addition, two larger-scale (diameter = 150 mm, height = 240–300 mm) falling-head *k* tests with tap water were conducted on remolded specimens prepared from grab samples collected at Stations 0 + 70 m and 0 + 90 m. These tests were conducted in rigid-wall cells made from plastic pipe. Pea gravel, wire mesh, and filter paper were placed above and below the specimens, and pressures of 3.5–21.7 kPa were applied in stages using weights placed directly on the upper gravel layer.

3.2 In Situ (Slug) Tests

Slug tests were performed to obtain postconstruction measurements of the *in-situ* backfill *k*. The slug test wells consisted of prepacked wells (GeoProbe, Salina, KS) installed by first pushing steel casing (diameter = 7.6 cm) with an expendable cone tip into the wall to the target depth, then inserting the well (a 61-cm-long section of slotted PVC encased in filter sand and steel mesh screen and attached to PVC standpipe; see Fig. 3) into the casing. The casing was then removed, allowing the soft backfill to seal against the well. Six test wells were installed in the test section (Fig. 1c) at depths ranging from 3 to 6 m.

The slug tests were conducted by placing a vibrating wire piezometer into the well, then adding a small volume ("slug") of water to the well to raise the water level from the initial static level H_{wt} to a new level H_p (see Fig. 3), and tracking the decrease in slug height H_s as the water level returned to equilibrium (see Fig. 4a). For this study, small slugs of water were added (initial slug height H_{so} = 25–69 cm) to avoid hydraulic fracturing of the backfill, given the low *in-situ* effective stresses (see Fig. 2). Normalized head dissipation curves (i.e., $H_sH_{So})$ were plotted on a semi-log scale versus time, and *k* was computed using the following expression:

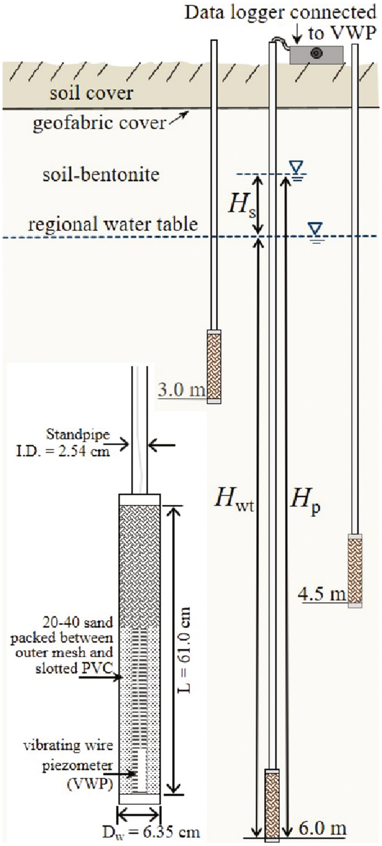

Fig. 3. Schematic of prepacked slug test well.

$$k = \frac{A}{M}m = -\frac{A}{F\Delta t}\ln\left(\frac{H_s}{H_{so}}\right) \tag{1}$$

where *A* is the cross-sectional area of the standpipe (see Fig. 3), *F* is a shape factor, and *m* [= $\ln(H_s/H_{so})/\Delta t$] is the slope of the normalized head dissipation curve (Fig. 4b). The shape factor, *F*, is based on the dimensions and depth of the well, and different methods for estimating *F* have been proposed in previous studies [5–10]. The shape factors proposed for SB walls by Britton et al. [8] were used in this study.

4 Results and Discussion

The results of all of the *k* tests performed for this study are summarized in Table 1. Values of σ' for the slug tests (8.7–11.2 kPa) represent the average *in-situ* effective stresses (mean of σ'_x, σ'_y, and σ'_z) estimated for each well based on Fig. 2. The volumes are the laboratory specimen volumes and the approximate backfill volume represented in the slug tests based on estimated effective radii of 29.7 cm [8]. Narrow ranges of *k* were obtained for a given test type and stress, indicating a high degree of homogeneity in the backfill. Most of the flexible-wall *k* values measured at the lower stresses (6.9–13.8 kPa), encompassing the range of *in-situ* stresses inferred at the slug test locations, ranged from 10^{-7} to 2×10^{-7} cm/s, whereas lower *k* values ($<10^{-7}$ cm/s in most cases) were measured at the higher stresses (20.7–34.5 kPa). The *k* values from the slug tests ranged from 1.3×10^{-7} to 3.3×10^{-7} cm/s, a range comparable to (though slightly wider and higher than) the range of flexible-wall *k* at the lower stresses. These results illustrate the importance of conducting lab *k* tests on SB backfill at stresses representative of the field stresses.

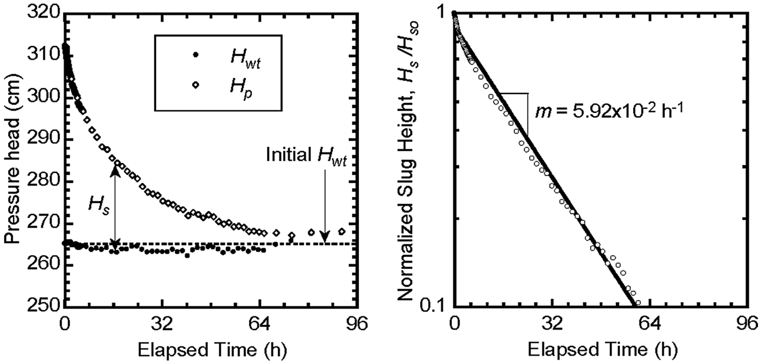

Fig. 4. Example slug test data for test well at Station 0 + 56.2 (depth = 4.5 m): (a) measured pressure heads versus time; (b) semi-log plot of normalized slug height (H_s/H_{so}) versus time.

Measured *k* values for each test type are plotted as a function of average σ' in Fig. 5. The flexible-wall *k* results for the remolded specimens are shown as averages with error bars denoting the minimum and maximum *k*. The undisturbed flexible-wall tests generally yielded *k* within but at the lower end of the ranges for the remolded specimens, whereas most of the *k* values from the slug tests and the rigid-wall tests lie above the flexible-wall *k* ranges. The slightly higher *k* values for the slug and rigid-wall tests suggest a possible scale effect, as the test volumes associated with these tests were considerably larger than for the flexible-wall tests. A similar effect was observed in the previous study by Britton et al. [1].

Table 1. Summary of hydraulic conductivity test results

Test type	No. of tests	Sample type	Volume (cm^3)	Station (m)	Depth (m)	a′ (kPa)	k ($\times 10^{-7}$ cm/s)
FWR	7	Grab	280–330	0 + 50 to 1 + 10	N/A	6.9	1.2–2.1
						13.8	0.93–1.6
						20.7	0.83–1.4
						34.5	0.70–1.1
RWR	2	Grab	4400–5000		N/A	3.5	5.1
						6.9	2.5–4.1
						13.8	2.1
						21.7	1.7–2.1
FWU		Tube	280–330			6.9	1.1–1.3
	1			0 + 67	2.1	10.2	2.5
	1			0 + 90	0.75	13.8	0.92–1.4
	3			1 + 10	2.0–3.5	20.7	0.80–2.3
						34.5	0.72–2.0
Slug	3	In Situ	83,200	0 + 56.3	4.5	8.7	2.1–3.0
	2			0 + 57.0	6.0	11.2	1.3–1.5
	1			0 + 57.6	3.0	11.2	2.7
	1			0 + 78.9	3.0	11.2	1.9
	1			0 + 79.3	4.0	9.4	2.0–2.1
	3			0 + 80	5.0	9.7	2.4–3.3

FWR flexible-wall tests on remolded specimens, *RWR* rigid-wall tests on remolded specimens, *FWU* flexible-wall tests on undisturbed specimens

Overall, the results indicate that slug testing is a useful method to determine the post-construction k of SB backfill. However, slug tests in SB walls require more time (e.g., 3–5 days) relative to a typical high-k aquifer (e.g., <<1 day). The longer durations introduce potential sources of error in the pressure data caused by changes in barometric pressure and fluctuations in the local groundwater table during the test. These sources of error were minimized in this study by (1) adjusting the pressure heads to account for barometric pressure changes based on hourly barometric pressure readings taken at an on-site weather station, and (2) adjusting the initial static water level (H_{wt}) in the test well based on measured changes in the water levels within the monitoring wells installed adjacent to the wall. Changes in H_{wt} should be minor if no precipitation events occur during a test (e.g., see Fig. 4a).

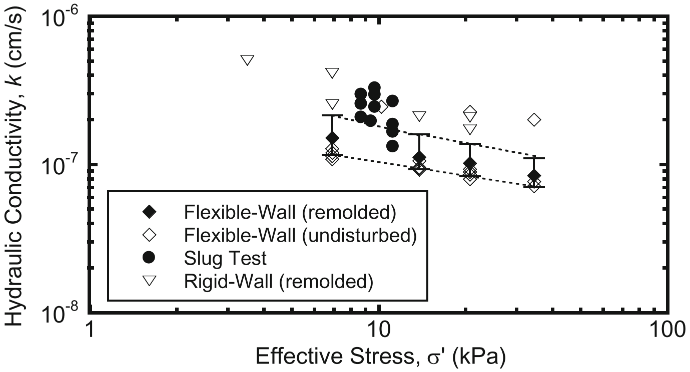

Fig. 5. Measured hydraulic conductivities plotted as a function of average effective stress.

5 Conclusions

The results of this study show that *in-situ* measurements of backfill hydraulic conductivity (*k*) obtained from slug tests in a field-scale soil-bentonite (SB) cutoff wall compare well with flexible-wall and rigid-wall laboratory *k* tests conducted on remolded or undisturbed backfill specimens at field representative stresses. The *k* values from the slug tests and the larger-scale rigid-wall laboratory tests generally were slightly higher than the flexible-wall *k* values obtained at similar stresses, indicating a slight scale effect associated with the larger test volumes in the slug tests and rigid-wall tests. Also, flexible-wall *k* values obtained at effective stresses greater than the measured field stresses generally were lower than the *k* values from the slug tests. This latter finding underscores the importance of conducting laboratory *k* tests at representative field stresses for SB walls, which tend to be lower than the stresses that would be predicted by assuming a geostatic stress distribution.

Overall, slug testing appears to be a viable method for determining the postconstruction *in-situ k* of SB backfill, provided that the measured pressure heads are adjusted to account for fluctuations in barometric pressure during the test. Fluctuations in the local groundwater table during the test also can be problematic if not accounted for, but can be minimized by avoiding precipitation events.

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